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EXPLORING A THEORY DESCRIBING THE PHYSICS OF INFORMATION SYSTEMS, INFORMATION PHYSICS EXPERIMENT PLAN

Zetetix

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EXPLORING A THEORY DESCRIBING THE PHYSICS OF INFORMATION SYSTEMS, INFORMATION PHYSICS EXPERIMENT PLAN

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13. ABSTRACT *(Maximum 200 words)*
This project accomplished all of its objectives: document a theory of information physics, conduct a workshop on planning experiments to test this theory, and design experiments that validate this theory. Information physics proposes quantitative relationships between observable information flows and changes in the content information systems maintain. This theory explains all flows within information systems as either diffusive or force-driven. The forces driving information flows arise from the existence of goal content. The workshop participants discussed various theories and considered experiments that characterize the macroscopic phenomena underlying complex information system behavior. These participants identified experimental opportunities that exploit existing databases, execute simulations and conduct traditional controlled experiments. They recommended that focussed experiments to test theories explaining information system phenomena were feasible today. The experiment plan builds upon the workshop's result and proposes experiments that measure information device energy dissipation, test the independence of symbol execution work from device efficiency, measure information diffusion rates in information systems, and measure force-driven information flows. These experiments are both technically and programmatically feasible. When validated, the proposed theory can guide designers to reliably build more effective, secure and predictable information systems.

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Abstract

This plan proposes four experiments that systematically, quantitatively and objectively explore the behavior of information systems:

- Device energy dissipation rates,
- Symbol execution work,
- Force-driven information flows, and
- Information diffusion rates.

These experiments cover a wide range of the hypotheses suggested in Volume I of this report. They also explore a variety of experimental techniques including formal controlled experiments involving single information devices, controlled experiments involving a large scale information system, and previous observations of very large scale information systems under both controlled and operational circumstances. Together these experiments will validate or refute the proposed hypotheses about information system behavior. But, they go even farther by establishing a cornerstone of lessons learned about scientifically exploring the macroscopic phenomena of large scale information systems upon which other such efforts can build.

Introduction

Volume I of this report proposes a model of information systems that could explain information system behavior at several different levels of abstraction. This model suggests several hypotheses that require empirical validation to assure its usefulness. These hypotheses take the first step in the scientific process. The next step is an experimental one. The results from these experiments can then be used to characterize the accuracy of this model's results and improve the model where its predictions are inaccurate or incorrect.

This volume describes the elements of four experiments that take the next step in this process. Each of these experiments examines a different aspect of the proposed model. This plan outlines only one approach to experimentally testing the model's hypotheses. Others may exist.

Experiment Descriptions

This plan considers four different experiments:

- Device energy dissipation rates,
- Symbol execution work,
- Force-driven information flows, and
- Information diffusion rates.

Each of the descriptions below follows the same format by describing the

- Experiment objective,
- Observed system description,
- Experiment procedure, and
- Observation/measurement techniques and error sources.

The device energy dissipation rates and symbol execution work independence experiments are formal experiments executed under carefully controlled conditions. The force-driven information flows experiment relies upon observations of actual information system behavior when operating under actual conditions or under conditions controlled for other experimental purposes. The information diffusion rates experiment observes an existing large scale information system (the Internet) under semi-controlled conditions. This range of options explores the issues associated with performing experiments upon information systems as well as providing information about the validity of the proposed model. As a result, this plan, if executed, will contribute broadly to a base of experience that should make future information system experiments easier.

Device Energy Dissipation Rates

This experiment characterizes the energy dissipation rates of practical information devices in a formal and carefully controlled way.

Experiment Objective

Equation (16) in Volume I of this report suggests that the energy dissipated by an information device is given by

$$J_{NOi} = J_{N0i} + (J_{IEi} + J_{NJi}) \quad (1)$$

where J_{N0i} = energy flow the information device i dissipates independent of the information flow through the device, and

J_{IEi} = energy flow dissipated only because of the erasure of information.

J_{NJi} = energy flow the information device i dissipates as a function of the information flow through the device.

This experiment will measure the energy dissipated by actual information devices to determine whether Equation (1) sufficiently represents that behavior and, if so, under what conditions that representation applies.

Observed System Description

This experiment considers the predicted behavior of information devices, in particular one of the most ubiquitous information devices, the modern microprocessor system. The experiment will characterize the energy dissipated by actual devices under varying information flow conditions. These conditions will be imposed by executing programs with different instruction mixes and information erasure rates. These mixes and erasure rates will be characterized by examining the machine code produced by the programming language compiler and the implementation of that code on the microprocessor architectures being examined. In addition, this experiment will impose the following controls:

- Examine two different microprocessor families, one produced by Intel and one produced by Motorola, to ensure that the experimental results do not apply to a single implementation approach;
- Execute several different programs with well understood instruction mixes to ensure that the experimental results do not apply only to a limited set of instructions or erasure rates;
- Carefully control the instructions executed, information erased and time run for each experiment trial to assure that the microprocessor behavior during the trials is well understood within the context of the proposed model;

- Run the test programs directly upon the base processor system without an operating system or peripherals to eliminate the uncertainties that these elements introduce;
- Measure the unloaded processor dissipation rate to understand the contribution of a constant dissipation rate upon the energy dissipation measurements;
- Always operate the microprocessors within the same temperature range and be sure that that range is well within the operating temperature range suggested by the manufacturers to reduce the possibilities of thermally-induced anomalies from influencing the experiment results;
- Isolate only the processing and associated memory components within the calorimeter while keeping other components such as the power supply outside the thermally isolated volume to improve the signal to noise ratio of the thermal measurements; and
- Thermally isolate the experimental systems to reduce environmentally introduced uncertainties in the energy dissipation measurements.

Experiment Procedure

The proposed experiment will follow the steps below:

- Characterize the thermal leakage to and from the calorimeter by observing the temperature variations when beginning with a thermal mass at a temperature below and above that of the ambient environment;
- Enclose the microprocessor within the calorimeter, minimize the influence of the leads upon the thermal isolation, and characterize the effects of the leads upon the calorimeter's thermal isolation;
- Characterize the microprocessor's no load energy dissipation rate by operating it under power but executing no instructions;
- Characterize the microprocessor's energy dissipation rate by executing programs with varying instruction mixes that do not erase information;
- Characterize the microprocessor's energy dissipation rates while executing programs with varying instruction loads;
- Characterize the microprocessor's energy dissipation rates while executing programs with varying information erasure loads;
- Repeat the individual tests several times to gain significant statistical samples from which to characterize the magnitude of the systematic error contributions;
- Repeat this experimental procedure on microprocessors with two different processor architectures to understand the influence of different implementation approaches upon energy dissipation;

- Analyze the no load measurements to determine J_{N0i} for each of the tests and use the repeated tests of the no load measurements to characterize the error magnitude;
- Analyze the tests involving varying erasing loads to determine J_{IEi} for each of the tests and use the repeated tests of the erasure loads measurements to characterize the error magnitude;
- Compute J_{NJi} from the measurements of J_{N0i} and J_{IEi} for each of the tests and characterize the error magnitude from the derivatives of this function; and
- Compare the energy dissipation fluxes for the different microprocessor architectures under the different instruction loads.

Observation/Measurement Techniques & Errors

These experiments will employ the following measurement techniques:

- Microprocessor and calorimeter temperatures will be measured using commercially available and well characterized temperature probes.
- Microprocessor input power will be measured using commercially available current and voltage probes.
- Test execution times will be measured using the digital clock of the experiment management computer system.
- Instruction execution loads will be characterized by examining the compiled machine code of the test programs and tracing the execution of those programs through the microprocessor's architecture.

The time and temperature sensors as well as the processor execution will be operated under the control of an experiment management computer system that will collect and timestamp the measurements. It will also be used to analyze the data and characterize the systematic errors. In addition to these, the measurements of this experiment involve the following error sources:

- Temperature measurement errors associated with the sensor, usually characterized by the manufacturer;
- Input power measurement errors associated with the sensors, usually characterized by the manufacturer;
- Time measurement errors, determined by the resolution and drift rates of the experiment management computer;
- Calorimeter thermal leakage rates, characterized by tests that put known energy content into the calorimeter and measure the leakage of that energy; and

- Energy leakage through non-thermal means, limited by careful calorimeter construction and isolation, and characterized by comparing the energy dissipation measured and the energy input measured.

Symbol Execution Work

This experiment measures the independence of the work associated with executing symbols from the devices executing them.

Experiment Objective

Equation (23) in Volume I of this report suggests that the work performed by an information device depends upon the instructions it executes and that dependency is described by

$$W_{ij} = \eta_{Sij}\, w_j \tag{2}$$

where W_{ij} = the work device i invests to execute symbol j,

η_{Sij} = the efficiency with which device j executes symbol j, and

w_j = the normalized work required for any device in an information system to execute symbol j.

This experiment will characterize the dependency of the work performed by actual information devices upon the actual instructions they execute to determine whether Equation (2) sufficiently represents that behavior and, if so, under what conditions that representation applies.

Observed System Description

This experiment will use the same experimental arrangement as described in the device energy dissipation rates experiment. Many of the arrangement issues are the same for these two experiments. However, for completeness, these issues will be discussed under this heading, as well, even though this choice introduces obvious, and perhaps tedious, repetition for the reader.

This experiment considers the predicted ability to separate the contributions of instruction load and device inefficiencies to instruction execution energy dissipation. The experiment will characterize the energy dissipation load imposed by different instructions and the efficiency with which different processing device implementations execute those different instructions. These conditions will be imposed by constructing and executing programs that repeat loops containing the same instructions. Of course, this experiment will also require careful characterization of the way in which the different processor architectures actually implement these loops. In addition, this experiment will impose the following controls:

- Examine two different microprocessor families, one produced by Intel and one produced by Motorola, to ensure that the experimental results do not apply to a single implementation approach;

- Execute several different programs with well understood instruction mixes to ensure that the experimental results do not apply only to a limited set of instructions or erasure rates;
- Carefully control the instructions executed, information erased, and time run for each experiment trial to assure that the microprocessor behavior during the trials is well understood within the context of the proposed model;
- Run the test programs directly upon the base processor system without an operating system or peripherals to eliminate the uncertainties that these elements introduce;
- Use the unloaded processor dissipation rate, measured in the previous experiment, to understand the contribution of a constant dissipation rate upon the energy dissipation measurements;
- Always operate the microprocessors within the same temperature range and be sure that that range is well within the operating temperature range suggested by the manufacture to reduce the possibilities of thermally-induced anomalies from influencing the experiment results;
- Isolate only the processing and associated memory components within the calorimeter while keeping other components such as the power supply outside the thermally isolated volume to improve the signal to noise ratio of the thermal measurements; and
- Thermally isolate the experimental systems to reduce environmentally introduced uncertainties in the energy dissipation measurements.

Experiment Procedure

The proposed experiment will follow the steps below:

- Use the thermal leakage characterization to and from calorimeter produced by the previous experiment;
- Use the same experimental arrangement as proposed in the previous experiment that encloses the microprocessor within the calorimeter, minimizes the influence of the leads upon the thermal isolation, and characterizes the effects of the leads upon the calorimeter's thermal isolation;
- Use the microprocessor's no load energy dissipation rate that was characterized in the previous experiment;
- Use the microprocessor's energy dissipation rate from information erasure that was characterized by the previous experiment;
- Characterize the microprocessor's energy dissipation rates while executing programs that repeat the same instructions but do not erase information;

- Characterize the microprocessor's energy dissipation rates while executing programs that repeat the same instructions but do erase information;
- Collect data on the same instruction loops executed over different time intervals to characterize the initialization and completion effects;
- Repeat the individual tests several times to gain significant statistical samples from which to characterize the magnitude of the systematic error contributions;
- Repeat this experimental procedure on microprocessors with two different processor architectures to understand the influence of different implementation approaches upon instruction work dependencies;
- Compute W_{ij} from the measured energy accumulated by the calorimeter minus the energy dissipated by the no instruction load measured in the previous experiment;
- Use measurements from two different microprocessors to compute w_j and η_{Sij} for those processors for each instruction tested;
- Use these values of w_j to compute η_{Sij} for the other microprocessors tested; and
- Compare these values for η_{Sij} against the w_j's for different instructions to determine if η_{Sij} remains constant for each microprocessor tested over the different instructions tested.

Observation/Measurement Techniques & Errors

These experiments will employ the following measurement techniques:

- Microprocessor and calorimeter temperatures will be measured using commercially available and well characterized temperature probes.
- Microprocessor input power will be measured using commercially available current and voltage probes.
- Test execution times will be measured using the digital clock of the experiment management computer system.
- Instruction execution loads will be characterized by examining the compiled machine code of the test programs and tracing the execution of those programs through the microprocessor's architecture.

The time and temperature sensors as well as the processor execution will be operated under the control of an experiment management computer system that will collect and timestamp the measurements. It will also be used to analyze the data and characterize the systematic errors. In addition to these, the measurements of this experiment involve the following error sources:

- Temperature measurement errors associated with the sensor, usually characterized by the manufacturer;

- Input power measurement errors associated with the sensors, usually characterized by the manufacturer;
- Time measurement errors, determined by the resolution and drift rates of the experiment management computer;
- Calorimeter thermal leakage rates, characterized by tests that put known energy content into the calorimeter and measure the leakage of that energy; and
- Energy leakage through non-thermal means, limited by careful calorimeter construction and isolation, and characterized by comparing the energy dissipation measured and the energy input measured.

Force-Driven Information Flows

This experiment explores the behavior of large scale information systems through the observations of others.

Experiment Objective

Equation (37) in Volume I of this report suggests that the strength of the goals maintained by an information system depends upon the information flow rates through its devices such that

$$E_G = I_{Ii} R_{Ii} \tag{3}$$

where E_G = magnitude of the force exerted by information system goals,

I_{IGi} = total information flow through device i caused by the existence of the information system's goals, and

R_{Ii} = device resistance to information flow.

Equation (40) provides the means to measure the resistance of information devices by measuring the dependence of the work they perform upon the rate of the information flowing through them such that

$$W_{Di} = I_{Ii}^2 R_{Ii} \Delta t \tag{4}$$

where W_{Ii} = work performed by the device i and

Δt = the time interval over which the information flow is sustained.

This experiment will characterize the dependencies of the goal forces upon information rates and of the work performed upon the device resistances to determine whether Equations (3) and (4) sufficiently represent that behavior and, if so, under what conditions those representations apply.

Observed System Description

This experiment will differ from all of the others described in this plan by examining existing data that characterizes the behavior of actual information systems. This experiment will also look at the behavior of information within an entire system rather than conducting controlled experiments on components of a system. Observations of two different systems will be considered,

- Information assurance experiment results, and
- Internet electronic commerce statistics.

As a result of exploiting existing data, no controls can be imposed to isolate the particular effects of interest. Instead, mathematical tests will be used to assess the statistical significance of the analysis results.

Experiment Procedure

The proposed experiment will follow the steps below:

- From the observations, identify each component involved in the operation and its connectivity to the other components of the system being explored;
- Use the information flow dependence of energy dissipation measured in the previous experiments to estimate a work factor for the electronic computational resources in these systems;
- Use physiological observations of the energy dissipation from the human brain to estimate a work factor for the human computational resources in these systems
- Partition the observations into tasks (e.g., the attack trees from the IA experiments provide this information directly);
- Determine the time interval each type of resource is used to accomplish each task;
- Multiply the task time interval by the work factor for each type of resource used to estimate the total amount of work, W_{Di}, expended for each task;
- Estimate the total information flows, I_{Ii}, for each task for each component from the experiment observations or usage statistics
- Compute the device resistances, R_{Ii}, for each resource involved from Equation (4);
- Identify the different information flows involved in each task from the observations or statistics;
- Identify the goals associated with each task from the nature of the task and the participants (e.g., for the IA experiments, one goal is to compromise the system; for

electronic commerce, buyers have the goal of buying something and sellers have the goal of selling something and separate goals exist for each product involved);

- From the information flows and the estimated device resistances, compute the goal forces, E_G;
- Compare the goal force values to assess their consistency in the context of the entire experiment or usage process;
- Perform analysis of observations for several different experiments and electronic commerce activities; and
- Apply statistical tests to determine the significance of the correlations found in analysis.

Observation/Measurement Techniques

This experiment will use data from the observations made by others. As a result, some effort must be expended to understand the limitations of those observations and the experimental techniques they employed. However, the specifics of this evaluation will depend upon the nature of the particular observations and experiments. As much as possible, statistical tests will be applied to their observations to ensure that the data used for this experiment is anomaly-free.

In addition to the error sources associated with the particular observations used, the following must be considered in this specific experiment:

- Errors in the estimates of work factors for electronic and human computational resources;
- Assuming that all humans have equal work factors; and
- Errors in associating individual information flows with individual tasks.

Information Diffusion Rates

This experiment measures the rate of information diffusion within a large scale information system.

Experiment Objective

Equation (41) in Volume I of this report suggests that the rate of information diffusion through an information system depends upon the relative information content density and a diffusion constant such that

$$I_{Di} = D_{Si}\, \nabla_T \rho_{Ii} \qquad (5)$$

where I_{Di} = rate of information flow due to diffusion across the boundaries of the information device or system i,

D_{Si} = diffusion constant for information through the system, and

$\nabla_T \rho_{Ii}$= topological difference in information density between the device or system i and the other components with which it has connectivity.

This experiment will characterize the dependencies of the information diffusion rate upon relative information content densities to determine whether Equation (5) sufficiently represents that behavior and, if so, under what conditions that representation applies.

Observed System Description

This experiment differs from the first two in that it explores the behavior of a large scale information system, the Internet. The purpose of this experiment is to characterize the phenomena of information diffusion. The hypothesis, presented above, suggests that information can flow through a system independent of, and often despite, any explicit intentions. To explore this phenomena, this experiment will locate some identifiable information upon a website and measure how long it takes for that information to reach the users of that website. This experiment will employ the following controls:

- Choose a unique piece of information that has no value to any of the users to reduce or eliminate the possibility of those users purposefully attempting to acquire the information;
- Refrain from telling the chosen user set about the actual purpose of the experiment to further reduce the possibility of their working to acquire the test information;
- Locate the test information so that it is not directly associated with the purpose of the website to the users involved;
- Construct the test administered to the users so that it does not betray the real purpose of the experiment to prevent the users from gaining an interest in searching for the test information; and
- Change the specific information after each test to determine its location within the user community.

Experiment Procedure

The proposed experiment will follow the steps below:

- Locate a unique piece of information on a website to which a set of users have access and an interest in accessing;
- After a measured time interval, test the user community to determine whether they possess that information either in their memory or in the persistent storage of their computer and how many times it occurs.
- After each testing, change the test information and restart the interval clock;

- Vary the time interval before testing to provide enough information to sufficiently distinguish the rate at which the information diffuses;
- Measure the number of times each user accesses the website to determine the number of contacts required for information to diffuse to them;
- Compute the information diffusion rate, I_{Di}, from the volume of information, the number of times it occurs on each resource, and the time required to reach the user base;
- Compute the difference in information density, $\nabla_T \rho_{Ii}$, from the volume of information contained by the website, the volume of information consumed by the test information, and the volume of information maintained by each user;
- Compute the diffusion constant from the computed values of I_{Di} and $\nabla_T \rho_{Ii}$ and Equation (5);
- Determine the consistency of these computed values over several repetitions of the same tests with the same user base;
- If possible, repeat the trials to gain sufficient data to statistically estimate the experimental errors;
- If the diffusion rate is rapid enough, repeat the experiment with different types and volumes of information to test the independence of the diffusion rate of information content; and
- If the diffusion rate is rapid enough, repeat the experiment with different sets of users.

Depending upon the size of the user base available, the information diffusion rates may be small and, therefore, require considerable time to characterize. If this is the case then several repetitions of the same experiment may be uneconomical and other experimental designs may be needed to gain a broader understanding of information diffusion phenomena.

Observation/Measurement Techniques & Errors

These experiments will employ the following measurement techniques:

- Use carefully designed questionaires that query users of the experimental website about the contents of their persistent knowledge, in both biological and electronic forms, to determine if they possess the test information;
- Test the user base after measured time intervals to estimate the information diffusion rate;
- Vary the measurement time intervals to improve the resolution of the diffusion rate estimate; and
- Count the number times each user accesses the website to determine the probability that they will acquire the test information.

These measurements will be subject to the following error sources:

- Limited resolution of the time interval measurement because of the discrete intervals between testing events;
- Testing errors that either fail to discover when users actually possess the test information or bias the users into exerting some intention to explicitly find the test information;
- Accidental accesses to the website that bias the probability of information movement;
- Choosing test information that is completely valueless to the entire user base included in the experiment; and
- Test information traveling some paths not characterized by the experiment (e.g., from one user to another).

Conclusions

This plan proposes four experiments to test the hypotheses characterizing information system behavior that were described in Volume I of this report. These experiments consider information system behavior at both the device and system levels. They also explore the behavior of several different information device components. The experiments in this plan build upon each other with the device experiments providing information for the system level experiments. As such, they represent a complementary group that takes the first step toward validating the proposed theory.

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